SMALL PROBES AS FLIGHT TEST BEDS FOR THERMAL PROTECTION MATERIALS

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ABSTRACT

Thermal Protection System (TPS) materials for atmospheric entry probes are traditionally tested and flight qualified in ground-based arc jet test facilities. Testing is performed using a family of test article geometries including blunt axisymmetric stagnation articles, blunt wedge articles, and large flat panel articles. Together these test geometries partially reconstruct aerothermal environment parameters predicted along a trajectory. The tests attempt to replicate environments predicted at a single location on the TPS, at a single time point on a trajectory. One strategy to strengthen the ground to flight traceability of a TPS certification program is to develop an affordable test platform comprised of fully instrumented small probes. This paper summarizes the results of a focused systems study of a class of small probes (8-24 kg entry mass and less than 40 cm in diameter) that can be tested on the ground and can be launched as secondary payloads, deployed in orbit, de-orbited and recovered on Earth.

1. INTRODUCTION

Thermal Protection Systems (TPS) are traditionally developed, designed, and flight certified based primarily on data collected from ground based tests. This approach is the best strategy available within the constraints of most projects and is an exception to the Test Like You Fly (TLYF) design philosophy (a philosophy in which one attempts to achieve both geometric and dynamic similitude between ground test and flight) because the environments simulated on the ground are only partial combinations of the environment parameters encountered in flight. In the process of testing and qualification for TPS materials, it is important to understand nominal material performance as well as failure modes and mechanisms in mission relevant environments because a TPS failure during entry will result in not only the loss of the mission, but in the case of a manned flight, it may result in loss of human life.

One way of relaxing the restrictions imposed by ground test facilities (mainly the inability to achieve perfect similitude to flight) is through flight test programs. However, flight tests are rarely performed not because of technical difficulties but primarily because of programmatic cost and schedule constraints that are imposed on a mission and technology development projects. Nevertheless, it is still worth exploring affordable flight test programs with the specific intent of raising the technology readiness level (TRL) of candidate materials.

The concept of a small probe as a flight test bed for TPS materials represents a compromise between a full-scale flight test and a coupon-scale ground test article. The probe would be designed to be as small as possible using existing off the shelf Entry Descent and Landing (EDL) technologies. The upper limit on the size of the probe is primarily driven by ground test article size constraints. Maintaining a 1:1 geometric similitude between the ground test and flight article would allow the same probe to be tested both on the ground and in flight at full scale; an innovative strategy that has the enormous potential to greatly increase knowledge and confidence in the TPS design at an affordable cost.

The objective of the present paper is to explore the feasibility and inherent benefits of developing a small probe concept to serve as a reliable flight test bed for thermal protection materials. A concept called

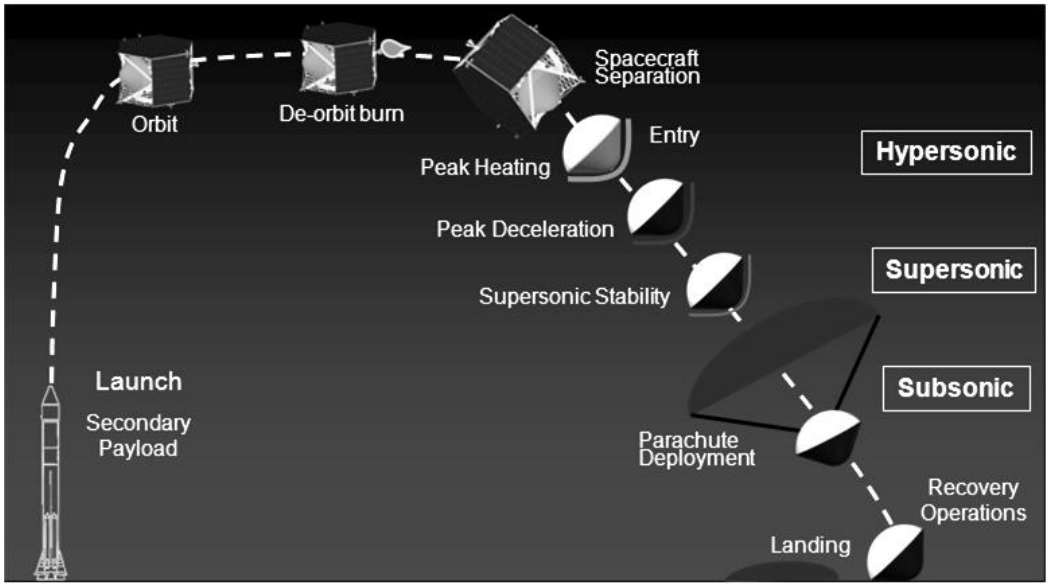


Figure 1. Concept of Operations for the SPRITE Mission

SPRITE (Small Probe Re-entry Investigation for TPS Engineering) is developed and discussed herein.

The paper is organized into three main sections. The first section provides an overview of the design concept for the SPRITE probe, the second sections describes the expected impacts to a TPS certification process, and the third section summarizes the expected impact on the TPS design process.

2. SMALL PROBE DESIGN

A key design goal is to make the SPRITE probe small enough to fit in a ground test facility at full scale and large enough to package the internal components such as a parachute, TPS instrumentation, data acquisition system, power system, ballast and tracking beacon. Maintaining consistent size and geometry between the ground and flight test articles enables an innovative test paradigm: if you can't test what you fly, then fly what you test.

Another key design goal is to utilize off the shelf technologies whenever possible to minimize cost and technical/programmatic risk. To keep launch costs low, the design would be developed as a secondary payload for an Evolved Expendable Launch Vehicle (EELV). The mission requires a spacecraft that performs all on-orbit functions required to keep the SPRITE probe operational while in space as well as to maneuver the entry capsule into the required entry trajectory upon command and separate from the SPRITE probe. After separation the spacecraft will take the necessary actions to insure that the hardware either burns up high in the atmosphere or lands in an uninhabited area such as the Pacific Ocean.

2.1. Concept of Operations

Figure 1 summarizes the sequence of events during a SPRITE mission. The probe would integrate with a spacecraft on the ground. The spacecraft provides all on-orbit functionality such as attitude control and orbital maneuvering (including the de-orbit maneuver directly prior to atmospheric entry). The complete SPRITE probe and spacecraft assembly would then be integrated with a secondary payload adapter and prepared for launch. After launch, the SPRITE probe and spacecraft would remain in Low Earth Orbit (LEO) until proper alignment with a predetermined landing site, upon which time the spacecraft would initiate a propulsive de-orbit burn and release the probe. The SPRITE probe would maintain passive stability through the hypersonic, supersonic and subsonic flow regimes. Once the probe reaches subsonic speeds, a parachute would be deployed to decelerate the probe to its landing velocity. A recovery team capable of tracking the probe would recover the probe hardware for post flight inspection and analysis of flight data recorded during entry.

Table 1. Summary of SPRITE entry conditions

	Ground Test	Sub Orbital	LEO	GTO
Entry Velocity	N/A	2 to 5 km/s	7 to 8 km/s	9 to11 km/s
Estimated De-orbit Delta V	N/A	N/A	200-300 m/s	<50 m/s
Est. Environments Q=**Stag. Heat (W/cm^2)** P=**Stag. Pressure (kPa)** S=**Frust. Shear (Pa)**	Q:50-400 P:0.1-12 S:50-250	Q: 100-200 P: 15-35 S:100-200	Q: 100-400 P: 10-25 S:100-300	Q: 800-1000 P: 20-50 S:300-600

2.2. Flight Design Reference Missions

Several design reference missions are possible with a single probe design including sub-orbital, LEO entry, and entry from a highly elliptical Geosynchronous Transfer Orbit (GTO). Combining the wide range of entry conditions with flexible ballasting options to control the probe's ballistic coefficient results in a spectrum of possible combined entry environments and heat load combinations which can be tailored to match specific exploration or robotic mission entry profiles. Table 1 summarizes the estimated environments and de-orbit delta V requirements.

2.3. Small Probe Design Concept

The SPRITE capsule is comprised of seven primary subsystems: structures (STR), landing and recovery system (LRS), electric power system (EPS), communication (COMM), command and data handling (C&DH), instrumentation (INST) and thermal protection system (TPS). Figure 2 illustrates the SPRITE probe design concept with all of the major components labeled.

The structure is designed to maintain structural integrity of the probe throughout all phases of the mission including launch, entry and landing. The current design concept for the structure includes a

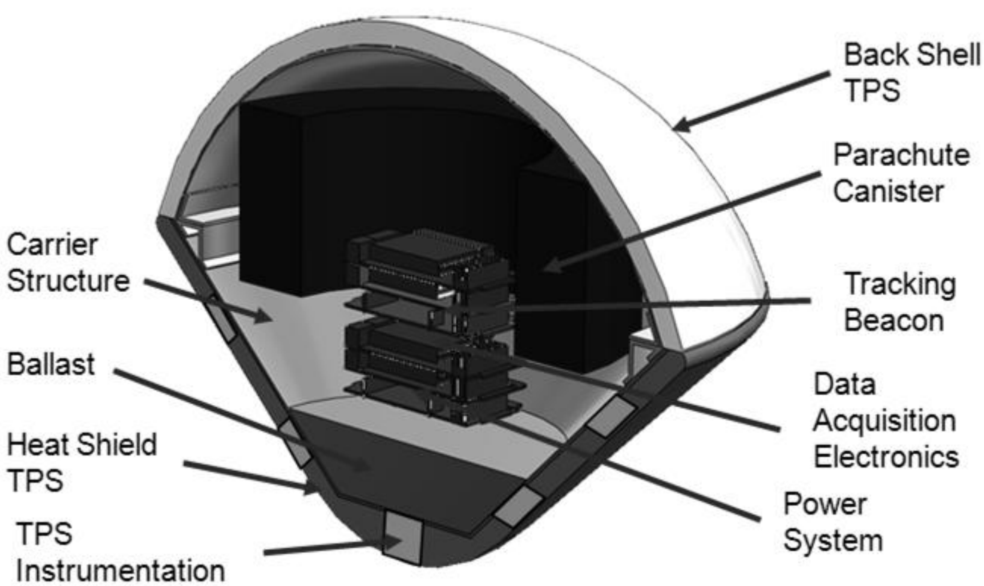


Figure 2. SPRITE probe packaging concept design

metallic or composite shell with fasteners that hold all of the internal hardware in place. Another function of the structure is to insure that the mass is distributed such that the entry probe will be stable for all phases of entry. A ballast mass is included in the nose of the probe to insure stability and give mission designers the flexibility to specify the total probe mass and therefore the ballistic coefficient.

The landing and recovery system is required to decelerate the probe to a safe landing velocity. A drogue parachute is used to stabilize the probe and deploy the main parachute. Both parachutes can be packaged in the toroidal volume as illustrated in Figure 2. A mechanism or pyrotechnic device will eject a section of the backshell to expose the parachute canister to the atmosphere prior to deployment.

The instrumentation system will include 5-10 TPS instrumentation plugs. The plug design is based on the MSL Entry Descent and Landing Instrumentation (MEDLI) design developed for the MSL heat shield. Each plug consists of 4 thermocouples and a Hollow aErothermal Ablation and Temperature (HEAT) sensor that is capable of tracking an isotherm as it penetrates the TPS material. The location of the isotherm can be correlated to the recession of the TPS [1].

The C&DH system will initiate the parachute deployment event and log all instrumentation data during flight. The EPS will supply all internal electronics with power during entry and after landing. The COMM system will transmit a radio signal that will be used to track the probe during entry and pinpoint the location after landing. The C&DH, COMM and EPS system hardware can be assembled from almost entirely off the shelf hardware developed for the small satellite community. A custom instrumentation interface board will interface with the main C&DH hardware.

The TPS material can be specified and sized to meet the requirements of the specific mission objectives of each flight.

Preliminary estimates indicate a minimum entry mass between 8-12 kg is feasible using off the shelf components and by using ballast weights the entry mass can be increased up to 20-25 kg to tailor the ballistic coefficient according to specific test requirements.

3. THERMAL PROTECTION TECHNOLOGY CERTIFICATION

Thermal protection system materials are almost always certified for flight based on testing in ground test facilities such as arc jets. There are generally three categories of ground based tests that comprise a certification program: development, qualification, and acceptance. Each phase in the certification process may benefit from the SPRITE ground or flight test bed.

During the development testing, ground tests are performed to show that the material (and design features) will perform over the broad range of environments expected during flight. Due to facility limitations and programmatic constraints only a partial set of conditions and features are tested. Broadening the combination of environments and the size of the features could improve confidence in the knowledge of the material behavior early in the development process. Development testing can also be used to establish acceptance and failure criteria based on test data. Large scale ground or flight based testing can be used to establish and justify the specific criteria that are used to verify the design and accept hardware.

Since TPS requirements are verified through analysis, qualification testing is predominantly used to validate models and the details of design features. Traditional ground based tests can only simulate partial combinations of environments, and the material response models are validated over a partial combination of the environmental parameters predicted in flight. These environments also limit the physical dimensions of the design features that can be tested for validation of feature specific models. Again, broadening the set of combined environments and the size of the features would improve confidence in model and design validation.

Acceptance testing is meant to ensure that the as-build design meets the specifications and is traceable to the qualification test hardware that was used to verify the design. Using large axisymmetric articles with relatively high surface area is a way to test a

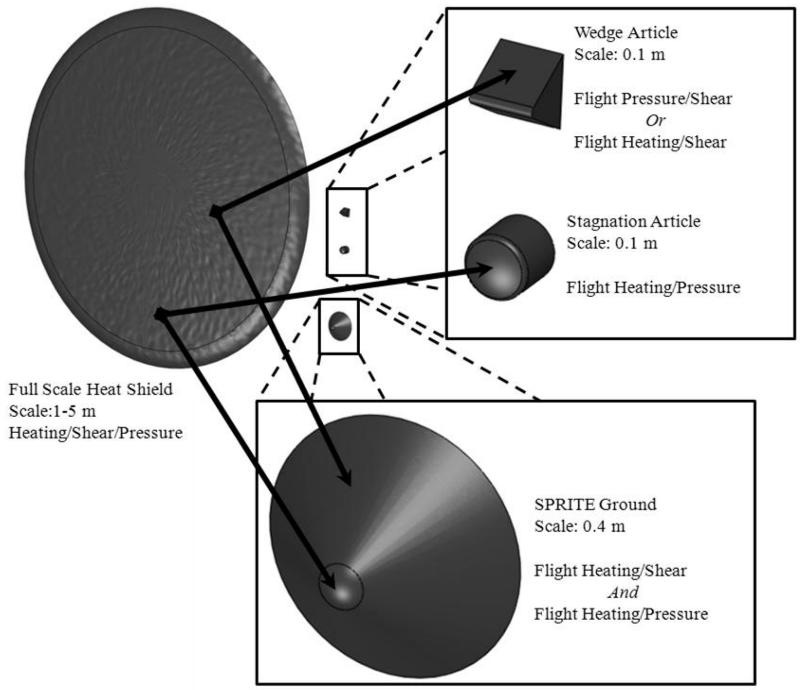


Figure 3. Summary of traditional coupon based ground test strategy

large number of acceptance coupons in a consistent environment, in a single entry of the test article in the arc jet flow field.

SPRITE can be used not only to flight certify TPS materials, but also the instruments that are used to measure material response and quantify the test environments. An affordable platform to raise the Technology Readiness Level (TRL) of TPS technologies could enable more flight instrumentation and thus improve environmental and material behavior knowledge for TPS design.

3.1. Ground Test Strategy

The ground test strategy is based on decomposing the flight environments on a single point on a flight scale heat shield, for a single point in time into two-three test configurations that each exposes the material to a sub-set of the combined environments. Two commonly used test configurations are axisymmetric stagnation articles and a blunt wedge. Stagnation articles are used to simulate a range of heat flux and pressure combinations where the wedge is used to simulate a combination of shear and pressure or shear and heat flux. In order to achieve statistical significance, each test must be repeated. However because of significant environmental uncertainty it is difficult to isolate anomalies observed during tests. Therefore the strategy outlined results in the need for a large number of arc jet tests. Because of limited resources, only a portion of the overall test environments are tested in this way and the points that are tested are carefully selected to bound the extremes of the expected flight environments, and sample the core operating conditions.

Testing in combined environments on the ground can greatly improve our understanding of the material behaviors in these environments as well as the potential failure mechanisms that may result in failure of a TPS design. This has been found to be especially true for glassy ablators such as SLA-561V [2] and Avcoat.

The SPRITE scaled ground test strategy is to select several points on the flight heat shield and test them on a single arc jet test article. Since the SPRITE test configuration is axisymmetric a relatively large surface area could be exposed to the same conditions for the same period of time thus reducing environmental uncertainty between coupons and improving the statistical significance of the material response data.

A demonstration of large scale test articles was performed as part of the Orion TPS Advanced Development Program (ADP) in 2008-2009 [3]. This test series demonstrated the significant benefits of large scale testing for material performance and failure mode characterization.

A second demonstration of the ability of arc jet facilities to test articles at flight scale, a full scale SPRITE model made out of red oak was tested in the Aerodynamic Heating Facility (AHF) at Ames Research Center (ARC) in fall of 2009. Figure 4 shows a comparison between the pre test flow field predictions and the observed characteristics of the flow during the test. Not only was the facility capable of capturing the hypersonic flow in the diffuser, but the pre-test computations predicted precisely where the flow separated on the back shell of the SPRITE model. The separation line can be seen in Figure 4 as the interface between the char and virgin wood coloring pattern.

The SPRITE test configuration does have limitations and is not intended to replace existing components of ground test strategies. Instead, SPRITE is designed to augment and enhance the type, quantity and quality of the data collected during TPS certification.

One limitation of the SPRITE test configuration is the upper limit of achievable heating, and pressure combinations of a SPRITE article in current ground test facilities. To accommodate large test articles, larger arc jet nozzles are required to avoid un-starting the facility. The larger nozzles effectively reduce the heat flux and pressure combinations achievable in test. One way to mitigate environmental limitations is to augment the current ground test facility capability space with arc jets capable of higher flow rates and higher power operation.

3.2. Flight Test Strategy

Generally three sets of variables can be adjusted to achieve TPS flight test objectives: combined environments, total heat loads, and characteristics of design features. Each type of flight test is tailored to interrogate a unique set of test objectives based on the needs of the certification program.

Combined environments include the aerothermal environments during entry as well as the thermal environments prior to entry and other natural environments. Testing extreme combined environments can give confidence that the flight design can perform in the most extreme environments and that the material selection and basic system design is valid. Though testing in extreme

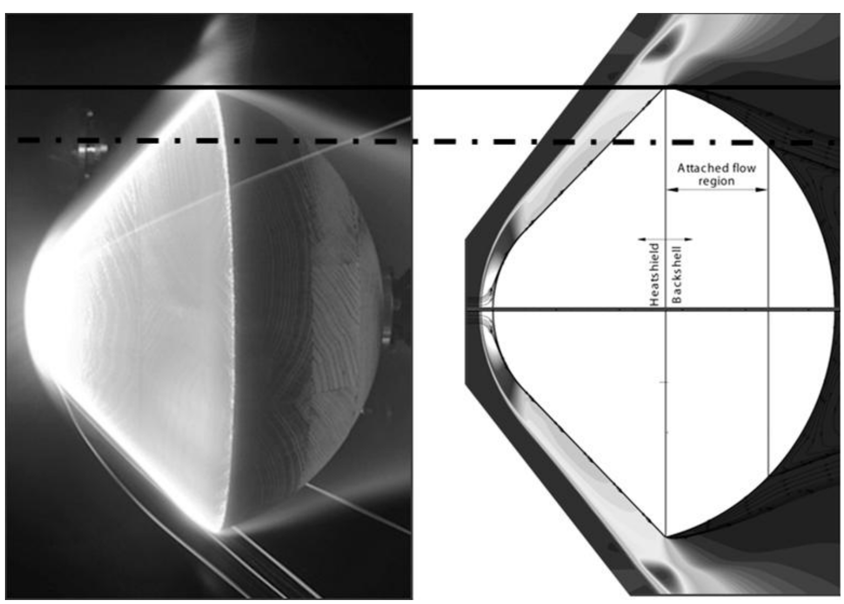
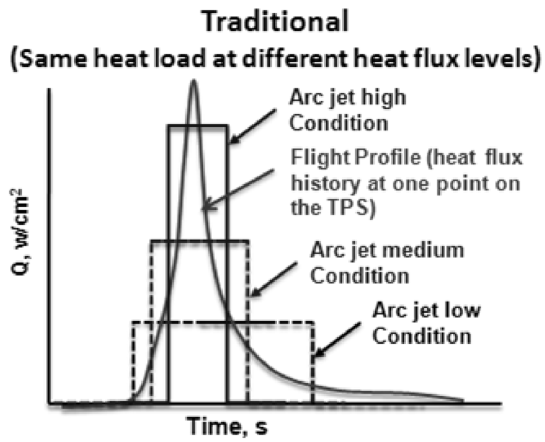
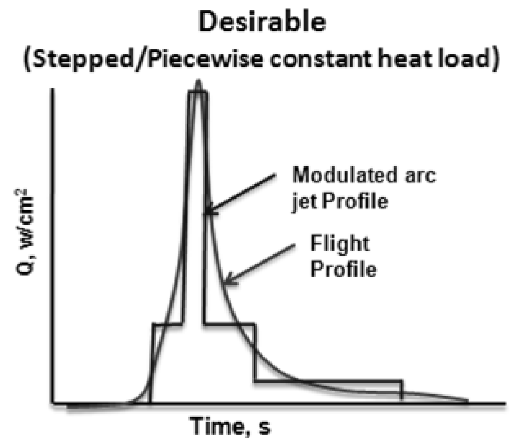


Figure 4. Test results and pre-test flow computations



(a)



(b)

Figure 5. Ground based testing techniques (a) traditional single condition steady test (b) multi-condition transient profile test

environments does give feedback about the overall design performance, it is not meant to investigate the overall thickness or size of the features.

The second class of flight tests includes subjecting the design features to high total heat loads. Results of this class of test can be used to show that the TPS design is sized to accommodate the range of heat loads possible during entry without over or under sizing the TPS.

The third class of variables is the state of the design during entry. There is potential in any TPS design for damage/defects to be introduced during manufacturing, assembly, in flight, and repair. Each type of known defect has an acceptance criteria based on geometry. These defects can be difficult to test in relevant environments on the ground. A flight test of a vehicle with pre-manufactured design defects can be used to validate the defect acceptance criteria in relevant environments to ensure the safety and effectiveness of the design.

Each of the three classes of flight test variables can be tailored and combined on the SPRITE test platform to meet the specific needs of the certification program. The reduced cost of the SPRITE platform compared to traditional flight tests mean that more testing in flight environments may be feasible for more missions. This additional flight test experience if designed and executed intelligently translates directly to a more efficient and robust TPS design.

Another limitation of current ground based tests is the steady state nature of traditional test conditions. In flight, a transient pulse of heat flux, pressure, and shear (among other parameters) sweeps over the TPS material. It is difficult to modulate the level of the heating and pressure concurrently in existing arc jet facilities and the test environments at each step in a profile tests have high aerothermal uncertainties. Because of these limitations, a single steady condition test approach has been traditionally adopted as seen to the left of Figure 5.

An example of why testing in a transient flight profile is important when correctly modeling the behavior of the TPS is when the low heat flux portion of the heat pulse melts on the surface of an ablator which will change the surface properties of the material during the high heating portion of the trajectory. A single condition test may not reveal this type of phenomena. In order to fully understand the behavior of the material in a flight like heating profile a capability to test in this type of environment is needed. An affordable scaled flight test is one effective way to study transient material response.

Modeling shape change of test article and flight vehicle geometry is another challenge for TPS designers. The coupling of the geometry to the environmental conditions creates a feedback loop that is difficult to model. The data collected from the SPRITE test platform will provide information necessary to develop and validate emerging techniques to model shape change on flight vehicles.

3.3. Coupling Ground and Flight Test

The key strength of the SPRITE platform is the ability to not only give engineers and researchers access to flight test data and augment/improve ground based data, but also to link the two types of tests directly. The aerothermal environment in an arc jet is different from flight in some important ways. For example, in order to match the expected flight enthalpy, the flow is electrically excited by passing high current through the test gas. In flight, the high levels of enthalpy are achieved almost entirely through shock heating of gas flows of high kinetic energy.

Another key difference between ground and flight is the composition of the flow field. In an arc jet test, a combination of air, nitrogen, oxygen and argon is used and the combination is not always representative of the composition of the flight flow field. This approach can have very strong influence on the material performance due to differences in oxidation rates. These examples, among others, form the motivation for flying what we test – a paradigm shift in TPS material certification that has the potential to build direct ground to flight traceability. This can give researchers the tools to understand the differences between the ground and flight environments and how the TPS materials behave in each environment. The result of this improved traceability is a more robust, and efficient TPS design.

4. THERMAL PROTECTION SYSTEM DESIGN IMPROVEMENTS

The objective of the TPS design process is to develop a design that is not only efficient in terms of mass but also robust enough to survive off-nominal events that may occur during a mission. More often than not, there is a significant amount of engineering judgment involved in reducing and quantifying design uncertainty while trying to strike a delicate balance between performance and reliability. In particular, the TPS sub-system has considerable design uncertainty because of the extreme nature of the environments and the uniqueness of TPS design challenges.

Design uncertainty can be divided into four major categories for ablative TPS: trajectory dispersions, aerothermal uncertainty, material properties uncertainty, and for the case of ablators, recession performance. The trajectory and aerothermal uncertainties are specific to the geometry and design trajectory of the full scale entry vehicle but the material property and recession uncertainty may be investigated with the SPRITE platform (either via ground or flight test).

By placing a relatively large set of coupons on the same test article in an axisymmetric pattern, the effect of material property variation can be studied directly with minimal environmental uncertainty from coupon to coupon. The environments of ground based testing of the SPRITE platform is limited by facility constraints, however if the flight platform is affordable, a much wider range of test conditions is achievable through flight tests. Both ground and flight test data have great potential to improve the thermal property margin by reducing environmental uncertainties during test, thus isolating the thermal behavior induced by the variation in properties alone.

In the case of ablators, the recession margin is designed to account for mechanical removal and other non-modeled material removal processes that may occur in flight but have not been observed during ground testing. A catalyst for mechanical removal of TPS materials is spallation induced erosion. The spallation products from upstream can contribute to increased recession rates. Due to the limited size of traditional test articles, this phenomenon is difficult to quantify. The SPRITE platform contains both stagnation and shear test articles in one package and the size is large enough to investigate and quantify upstream induced recession phenomena thus providing some data to support recession uncertainty.

Another example of material behavior for which adequate models do not exist currently is the flow of liquid glass (from a silicaceous ablator) from an upstream source on a streamline. SPRITE testing can improve knowledge of recession uncertainties but may not completely characterize all recession phenomena, some of which may be specific to flight geometry and flight environment characteristics.

In addition to contributing to the quantification of uncertainties, the SPRITE test platform can be applied to validate the process that is used to specify the TPS design. SPRITE flight data can be used to answer the question: does the TPS design process effectively treat the known and unknown design uncertainties to produce a design that operates within the specified performance limits? Using the SPRITE platform as a tool, the TPS design process can be formally and directly evaluated for performance in nominal and off nominal flight events. This assessment of the design process is another way the SPRITE platform can contribute to more robust and efficient TPS designs.

5. CONCLUDING REMARKS

SPRITE is designed to be a flexible, cost effective platform to improve and augment ground test data, provide relevant flight data early in development, and to build direct traceability between ground and flight data. All with the motivation to improve reliability and/or mass efficiency of modern TPS designs. The components of the SPRITE test platform include both ground based and flight test articles with the same geometry. Specifically the SPRITE platform provides the tools to:

- Collect reference data to challenge confidence in the thermal models and investigate governing physical phenomena (e.g. glass melt, coking and mechanical erosion).
- Enable investigation of transient material response of in a flight profile test
- Directly correlate ground and flight data in order to qualify the applicability/relevance of ground test data
- Identify unknown failure modes and investigate the behavior of known failure modes
- Demonstrate new TPS instruments and post flight analysis techniques for full scale vehicles and large scale flight tests
- Collect data necessary to develop and validate techniques to model entry vehicle shape change during flight
- Collect statistical material response data and reduce environmental uncertainty from coupon to coupon

6. ACKNOWLEDGEMENTS

The initial development of the SPRITE platform concept was supported by Ames Research Center management and workforce including the Space Technology Division (Charles Smith), Systems Analysis Branch (Mary Livingston), Engineering Directorate (Peter Klupar), and Experimental Aero-Physics Branch. Some of the key contributors to the SPRITE were from Georgia Tech students (Jessica Juneau, Bryan Chan, Stephanie Stout, Kento Masuyama, Nicole Bauer, and Milad Mahzari lead by Prof. David Spencer) working in collaboration with the ELORET Corporation supported by a Phase 1 NASA SBIR. Initial testing and prototyping was supported by George Raiche and Joe Olejniczak. The red oak model test was coordinated by Mark Loomis with fluid modeling performed by Dinesh Prabhu (ELORET Corp.) and the mechanical design by Sergey Gorbunov (Jacobs Technology Inc.). James Arnold and Dean Kontinos also provided leadership and advice throughout the concept development.

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